# Comparison of Modal Behaviour of Integral Abutment Bridge With and Without Soil–Structure Interaction

**Sreya Dhar and Kaustubh Dasgupta**

**Abstract** Integral abutment bridges (IABs) have gained popularity over past few years. The main advantage of IAB over conventional bridges is the absence of any bearing at the deck–abutment junction which leads to reduced possibility of unseating of bridge deck during strong earthquake shaking. The seismic response of bridges with integral abutments depends significantly on the abutment–soil interaction in the longitudinal direction and soil–pile interaction in the transverse direction. In the present study, the modal behaviour of IAB is investigated with and without the presence of soil–structure interaction (SSI). The soil flexibility for soil–pile and abutment–backfill interactions is represented by springs. This leads to significant increase in the overall flexibility of the bridge system as compared to the model with all the degrees of freedom (DOFs) restrained at the bottom of pier. Due to higher longitudinal stiffness contributed by both the deck and the abutments, the SSI bridge model shows complete longitudinal mode of vibration in higher mode. By removing the abutments and end spans of the deck, the first longitudinal mode of vibration occurs in one of the lower modes. Hence, the numbers of spans in the bridge play an important role in the modal behaviour of the bridge. The importance of SSI in modal analysis highlights its need for inclusion in the seismic design of IABs.

**Keywords** Integral abutment bridge · Soil–structure interaction
Modal analysis

S. Dhar (✉) · K. Dasgupta
Department of Civil Engineering, Indian Institute of Technology Guwahati,
Guwahati 781039, India
e-mail: sreya.dhar@gmail.com

K. Dasgupta
e-mail: kd@iitg.ernet.in

# 1 Introduction

Soil–structure interaction is an important aspect in the investigations of structural behaviour for carrying out performance-based earthquake engineering studies. Particularly, in the case of bridges, SSI along with multi-support excitations during earthquake shaking plays an important role in the seismic behaviour of a bridge. In urban areas, IABs are now becoming very popular due to minimal maintenance costs over their service periods. In typical bridges, the repair and maintenance of the joints and the bearings affect the life cycle cost of the bridge and overall economy [1, 2]. One of the most common problems of traditional bridge construction in seismic zone is unseating of the superstructure from the support bearings. This problem is eliminated in integral abutment construction as there are no support bearings [3]. Past studies on integral abutment bridges have accounted for the stresses in different components arising from creep, shrinkage and temperature effects [4]. The length of the integral bridge mainly depends on the pile capacity, soil type and abutment movement due to intensity of temperature and seismic load and other factors [5]. Backfill soil properties influence the IAB behaviour significantly [4, 6]. The contribution of bridge abutments in the natural vibration behaviour of IAB was also observed to be significant [7].

The present study mainly focuses on the natural behaviour of IAB with and without considering the effect of SSI. The effect of the abutment on the modal behaviour of the structure has also been investigated.

# 2 Description of Model

## 2.1 Bridge Model

In the present study, the previously studied Humboldt Bay Middle Channel Bridge [8, 9] has been considered with certain modified characteristics. The modelling of the bridge is carried out using the computer program SAP2000 V16.0.0 [10] (Fig. 1). The bridge is 330 m long, 10 m wide and 12 m in height. The bridge superstructure is integrally connected to the abutments at the two ends. The height, width and the thickness of the abutments are 12 m, 10 m and 1.2 m, respectively. The superstructure consists of concrete deck slab which is resting on four precast prestressed concrete symmetric I-shaped girders. The cross-sectional area and the second moments of the areas are taken as 0.73 $m^2$, 0.49 $m^4$ (major axis) and 0.0094 $m^4$ (minor axis), respectively. The deck slab is 165 mm thick, and it is rigidly connected with girders by rigid links. The superstructure is resting on piers which are connected to deck by pier caps. The length and cross-sectional area of pier cap are 10 m and 4 $m^2$, respectively. The height and cross-sectional area of each pier are 12 m and 3.4 $m^2$, respectively. Each pier is supported on pile foundation with each pile group having five precast driven piles. Pile foundations are
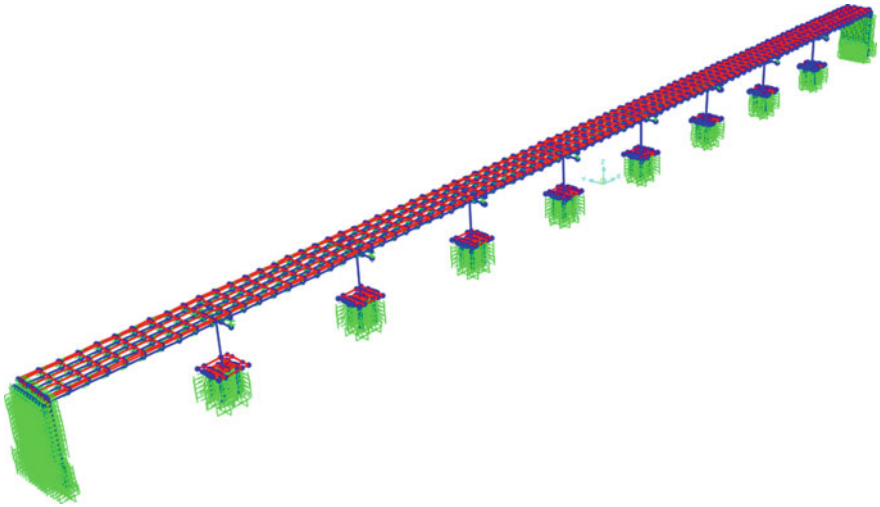
**Fig. 1** Modified Humboldt Bay Middle Channel Bridge with soil–structure interaction modelled in SAP2000

assumed to extend up to 5.2 m depth from ground level. The superstructure, pier and piles are discretized using two-noded frame elements with 6 degrees of freedom (DOFs) at each node, namely (a) three translational and (b) three rotational DOFs at each node. Each individual deck span is discretized into ten elements. Abutments and pilecaps have been modelled by linear elastic four-noded shell elements. Abutment piles have been modelled in the same way as the as pier piles, with a spacing of 1 m. The modulus of elasticity and unit weight of concrete are taken as 28 GPa and 24 kN/m$^3$, respectively.

## 2.2   Foundation and Abutment–Backfill

Springs have been used to model the flexibility of the backfill soil behind the abutments and the cohesive soil surrounding the piles (Fig. 1). For each spring, force–displacement curves have been used as per API-RP2 [11]. Piles are friction type or floating piles and have been incorporated with skin friction and lateral load resisting capacity due to surrounding soil. Both the lateral stiffness of the soil and the initial skin friction increase with the depth of the piles. The springs are also assigned to account for both the aspects. Each soil spring is modelled using one-noded link element in the program SAP2000 (Fig. 2a). At each pile tip, the end bearing resistance has been modelled by two-noded link element in SAP2000 (Fig. 2b). As the piles are of only 5.2 m in depth, they are considered to be short piles. Soil mass has not been considered for the present study while modelling soil–structure interaction of the IAB.
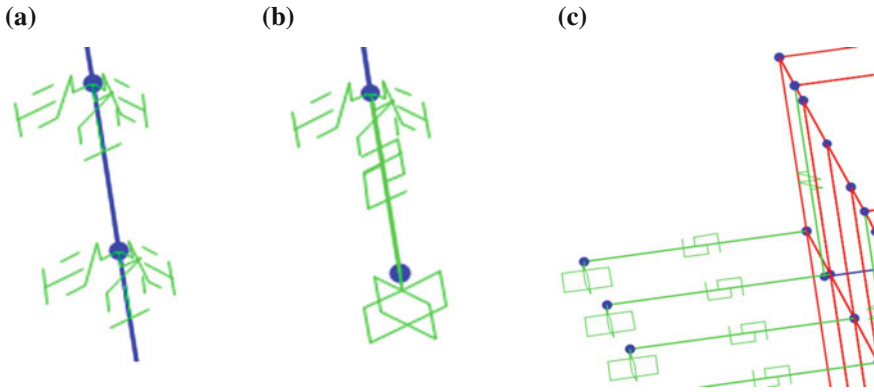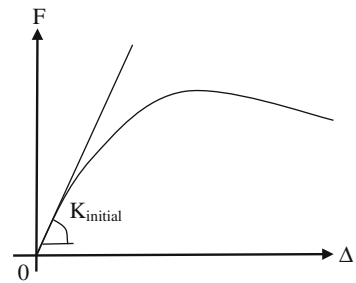
**(a)**                    **(b)**                         **(c)**



**Fig. 2** **a** One-noded horizontal and vertical link elements at different depths of piles, **b** two-noded link element at the tip of each pile and **c** two-noded link elements for modelling abutment–backfill interaction

**Fig. 3** Initial stiffness ($K_{initial}$) from the generic force–displacement curve of soil spring



Each abutment has been designed against the passive earth pressure during seismic excitation or temperature increment, since the active earth pressure is considered to be negligible [12]. Abutment–backfill behaviour has been modelled considering dense sand properties [8]. The lateral passive pressure exerted by the backfill soil tends to increase with the depth of abutment backwall. Abutment–backfill interaction has been modelled as per BA 42/96 [13] curves for end screen abutments of IAB. These properties have been assigned to the two-noded link elements (Fig. 2c). As linear elastic behaviour is required for the modal analysis, the initial stiffness has been considered for the soil spring elements from their nonlinear force–deformation curves (Fig. 3). For soil–pile interaction, initial lateral stiffness and skin friction are shown in Table 1. The initial lateral stiffness for abutment–backfill interaction is shown in Table 2. Only near-field soil–pile interaction has been considered.

Modal analysis of the bridge model has been carried out without the presence of piles, pilecap and soil and by considering the bottom nodes of pier as fully restrained. This model will be henceforth called as fixed base model. The same

**Table 1** Initial lateral stiffness of the soil and skin friction on pile at different depths

| Depth, m | Lateral stiffness, kN/m | Skin friction, kN/m$^2$ |
|----------|-------------------------|--------------------------|
| 1.0 | 250 | 2,497 |
| 2.0 | 250 | 3,248 |
| 3.0 | 250 | 3,973 |
| 4.0 | 748 | 4,587 |
| 5.2 | 748 | 5,228 |

**Table 2** Initial lateral stiffness for abutment–backfill interaction at different depths of abutment

| Depth, m | Initial lateral stiffness ($K$), kN/m |
|----------|----------------------------------------|
| 1 | 6,042 |
| 2 | 12,083 |
| 3 | 18,125 |
| 4 | 24,166 |
| 5 | 30,208 |
| 6 | 32,429 |
| 7 | 42,291 |
| 8 | 48,332 |
| 9 | 54,374 |
| 10 | 60,415 |
| 11 | 66,456 |
| 12 | 72,498 |

analysis has been carried out for the other model considering the soil–pile and backfill–abutment interactions. Modal analysis is carried out with initial zero-stress condition in soil which implies the absence of any other preceding static/dynamic analysis. Further, modal behaviour of IAB is also studied by removing end spans and abutments.

Hence, four cases have been considered to compare the modal behaviour of the bridge which are (a) only bridge model, (b) complete SSI model, (c) Case (i), where both the end spans with abutments have been removed from bridge and (d) Case (ii), where further end spans have been removed.

## 3  Comparison of Modal Analysis Results

For both the SSI model and the fixed base model, the natural periods and the mode shapes of the first 12 modes of vibration have been compared. The mode shapes of vibration for the first 3 modes are shown in Figs. 4, 5 and 6. The first modes are along the transverse direction of the bridge for both the models. Due to soil–pile interaction and increased flexibility, the entire pier cap–pier–pilecap–pile group system deforms along the height of the bridge. This results in less relative transverse deformation of the deck with respect to the bottom of pier in the
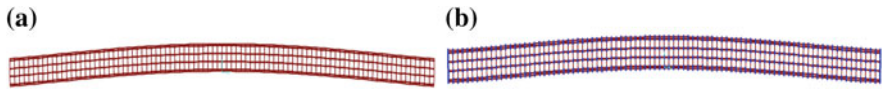
**Fig. 4** Plan views of first mode shape of vibration for **a** fixed base bridge model and **b** bridge with SSI model
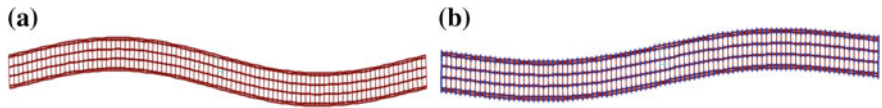


**Fig. 5** Plan views of second mode shape of vibration for **a** fixed base bridge model and **b** bridge with SSI model
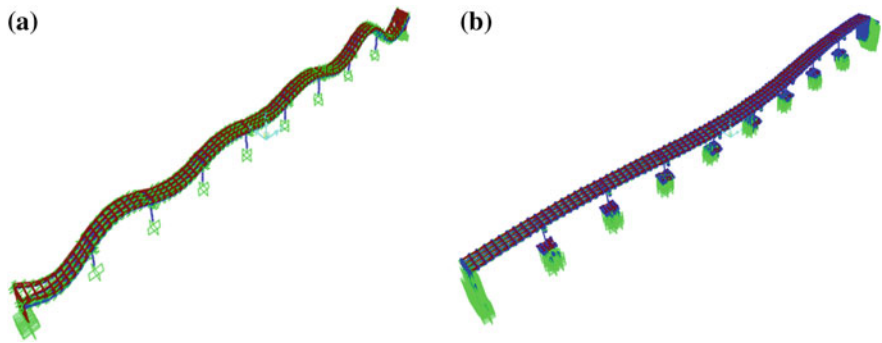


**Fig. 6** Plan views of third mode shape of vibration for **a** fixed base bridge model and **b** bridge with SSI model

corresponding mode shapes. However, in case of fixed base model, the variation of transverse deformation is steeper due to the large relative transverse deformations of deck with respect to the restrained bottom node of pier. For both the models, the second modes involve twisting of the bridge deck.

In the third and the fourth modes, the deck deforms in a wave-shaped profile in the vertical direction for both the models. For both the models, the contribution of longitudinal stiffness by the deck and the two abutments remains the same. However, in SSI model, the flexibility is increased due to the presence of pile cap–pile group–soil system below each pier. Further, the abutments of SSI model become relatively stiffer due to the presence of abutment–backfill interaction springs. The observation of the first longitudinal mode of vibration of the bridge depends on the relative influence of the combined longitudinal bridge stiffness (for the mentioned components) and the bridge stiffness along the transverse direction. Due to large difference between the two stiffness, the first longitudinal mode of vibration occurs in the 11th mode for the bridge model with SSI (Fig. 7).
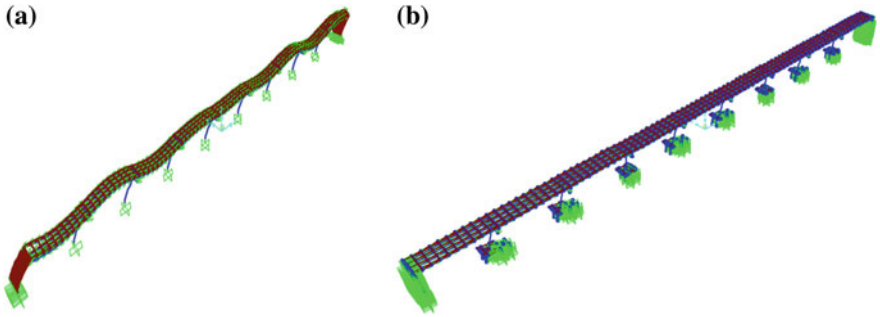
**Fig. 7** Longitudinal mode of vibration for **a** fixed base bridge model and **b** bridge with SSI model

**Table 3** Comparison of natural periods between fixed base bridge model and bridge with SSI model

| Mode no. | Time period, s | | | |
|---|---|---|---|---|
| | (a) Bridge model | (b) Full SSI model | (c) Case (i) | (d) Case (ii) |
| 1 | 0.697 | 2.136 | 2.216 | 2.190 |
| 2 | 0.651 | 1.654 | 2.070 | 2.020 |
| 3 | 0.549 | 1.282 | 1.897 | 1.864 |
| 4 | 0.547 | 1.066 | 1.651 | 1.274 |
| 5 | 0.540 | 0.912 | 1.060 | 0.900 |
| 6 | 0.494 | 0.865 | 0.891 | 0.860 |
| 7 | 0.493 | 0.852 | 0.858 | 0.840 |
| 8 | 0.464 | 0.840 | 0.849 | 0.774 |
| 9 | 0.457 | 0.833 | 0.838 | 0.764 |
| 10 | 0.452 | 0.815 | 0.777 | 0.761 |
| 11 | 0.434 | 0.802 | 0.767 | 0.760 |
| 12 | 0.410 | 0.776 | 0.762 | 0.747 |

As compared to the bridge with SSI model, the difference between the transverse bridge stiffness and the longitudinal bridge stiffness is lesser for the fixed base bridge model. This leads to the occurrence of the first longitudinal mode of vibration in seventh mode for the fixed base bridge model. For two-span integral bridge in underlying clayey soils, longitudinal modes of vibration were also observed in early modes in Ref. [6].

It is observed that the range of natural periods for the bridge model with SSI is higher than the entire range for the fixed base bridge model for the first 12 modes of natural vibration (Table 3). For higher modes, the natural periods are closely spaced for both the models. The presently studied bridge is expected to show significantly large response under earthquake ground motions with dominant period in the range of 0.8–2.1 s. However, the analysis of fixed base model shows an entirely different (lower) range for dominant periods of ground motions. Thus, using fixed base

bridge model for estimation of design forces may lead to unsafe design. Considering more realistic behaviour, SSI needs to be considered in performance-based bridge engineering studies.

## 4  Removal of End Spans in Bridge with SSI Model

Bridge abutments contribute more to the bridge stiffness along the transverse direction than the longitudinal direction due to their large length. In the present study, the contribution of abutments to the bridge stiffness is investigated by first removing the end spans of the bridge and the abutments (Case (i)). The increase in flexibility is observed for the first nine modes (Table 3) of the new bridge with increase in the natural periods. The bridge natural vibrations occur in transverse, torsional and longitudinal modes of vibration for the first three modes, respectively. Next, the two end spans of the reduced bridge were further removed (Case (ii)). However, the bridge response showed increase in stiffness for all the modes of vibration (Table 3). This is due to the reduction in the ratio of mass/stiffness for the entire bridge on removal of the spans. The nature of mode shapes of vibration for Case (ii) remains the same as in Case (i) (Fig. 8). Hence, the abutments and the number of spans of a bridge contribute to the relative magnitudes of transverse and longitudinal stiffness and hence play an important role in the modal behaviour of the bridge.

## 5  Summary

The present study is intended to compare the modal behaviour of an integral abutment bridge for two conditions, namely (a) the absence of SSI and (b) the presence of SSI. In the presence of pile cap–pile group–system and abutment–backfill interaction, the natural vibration characteristics of the bridge are quite different from those obtained through the conventional modelling approach, i.e., by restraining the bottom nodes of the piers. The contribution of abutments and the number of spans of the bridge have also been illustrated.

For both the cases, stiffness of the bridge along the transverse direction was lower as compared to the bridge stiffness along the longitudinal direction. This resulted in occurrence of transverse vibration configurations in the lower modes.
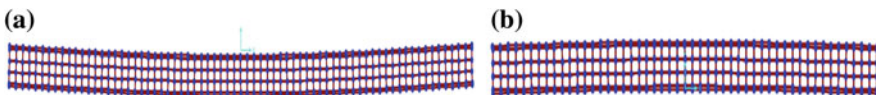


**Fig. 8** Transverse mode of vibration for **a** Case (i) and **b** Case (ii) models

Also, the components contributing to the SSI response of bridge influence the occurrence of longitudinal mode of vibration in the lower or the higher modes. The removal of abutments and the end spans brings changes to the mass/stiffness ratio of the overall bridge. This leads to some modes becoming stiffer and a few modes becoming more flexible.

The present study is carried out on the modified model of a real bridge for which extensive studies had been carried out in the past [8, 9]. To have more generalized conclusions, further studies need to be carried out on different bridge configurations with parametric variations. For longer bridges with more number of spans, heterogeneity of underlying soil becomes an important issue.

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